Transverse Spin Dependent Azimuthal Correlations of $\pi^+\pi^-$ Pair in $p^\uparrow p$ Collisions at $\sqrt{s}$ = 200 GeV at STAR

Overview

- Motivation
- Transversity in *pp*
- Cross-Ratio Formalism
- STAR Experiment at RHIC and Datasets
- IFF Results
- Summary

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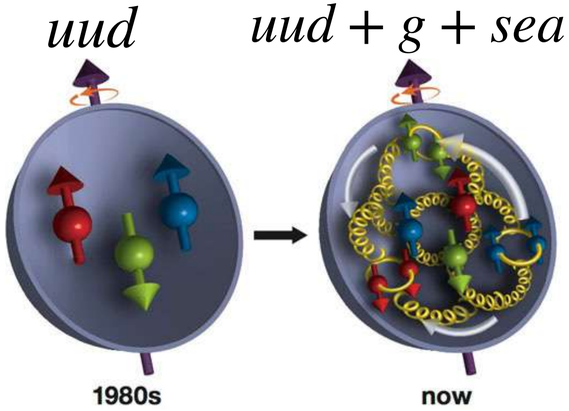
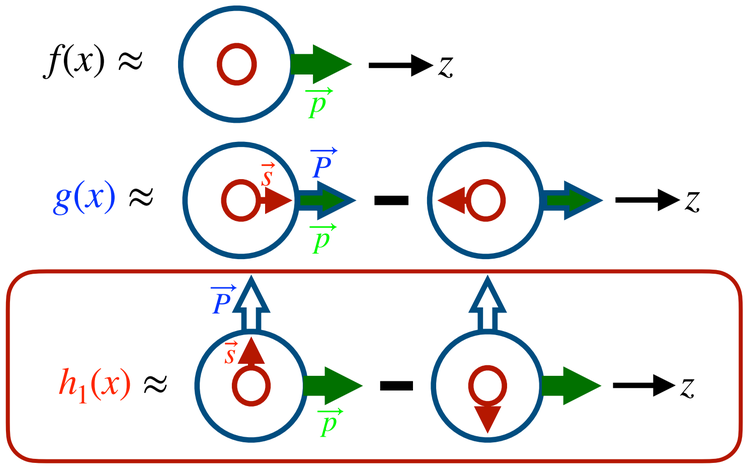
Motivation

Nucleon Structure:



Leading order parton distribution functions (PDFs):

$$f(x) \otimes g(x) \otimes h_1(x)$$



$\vec{P}$ = Nucleon polarization

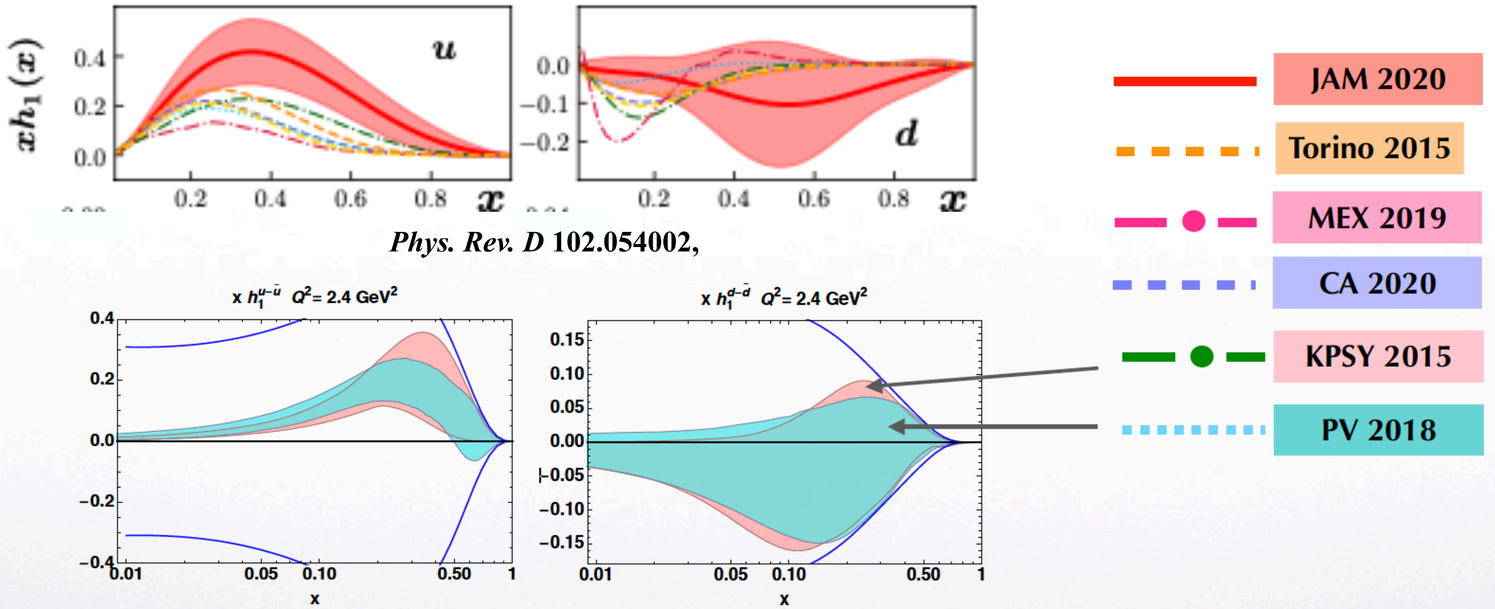
$\vec{p}$ = Nucleon momentum

$\vec{s}$ = Quark polarization

Transversity, $h_1(x)$:

- Chiral-odd quantity, independent measurement is difficult.
- Less known from experiments than $f(x)$ and $g(x)$.
- Its extraction requires coupling to another chiral-odd object, such as Fragmentation Function (FF).

M. Radici, Cracow School of Theoretical Physics, 2021



Phys. Rev. D 102.054002,

Phys.Rev.Lett. 120 (2018) 19, 192001

Transversity ($h_1(x)$) in $p^{\uparrow}p$ Collision, Coupling with FFs

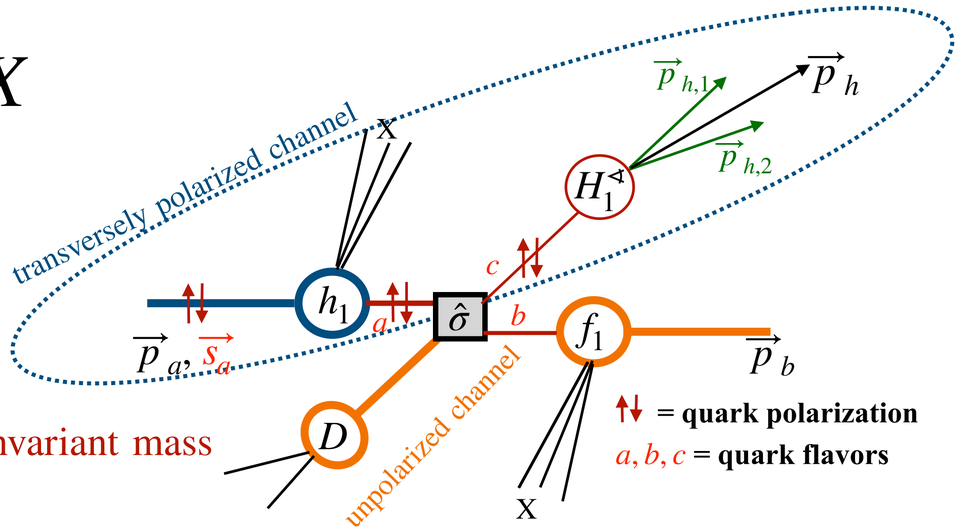
Bachhetta & Radici et al.
Phys.Rev.D 70 (2004) 094032

$$p^{\uparrow} + p \rightarrow h^{+}h^{-} + X$$

$$d\sigma_{UT} \propto sin(\phi_S - \phi_R) \int dx_a\, dx_b\, f_1(x_a) \boxed{h_1(x_b)} \frac{d\Delta\hat{\sigma}}{d\hat{t}} \boxed{H_1^{\sphericalangle}(z, M)}$$

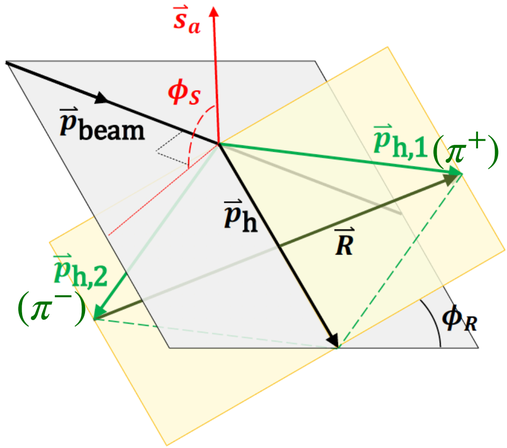
$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto h_1 H_1^{\sphericalangle}$$

$z = \frac{E^{h^+h^-}}{E^{parton}}$, M = Invariant mass



Di-hadron correlation asymmetry

- **Di-hadron Interference Fragmentation Function (IFF).**
  - Chiral-odd.
  - Independent extraction is possible in semi-inclusive DIS.
  - Helps to isolate h_1.



Azimuthal angle definitions:

- ϕ_s = angle between quark spin vector, $\vec{s}_a$, and scattering plane (spanned by $\vec{p}_{beam}$ and $\vec{p}_h$)
- ϕ_R = angle between scattering plane and di-hadron plane (spanned by $\vec{p}_{h,1}$ and $\vec{p}_{h,2}$)

- No jet reconstruction required.
- Collinearity is preserved.
- In STAR, although both beams are polarized, single spin asymmetry is achieved by integrating over the polarization of the other beam.

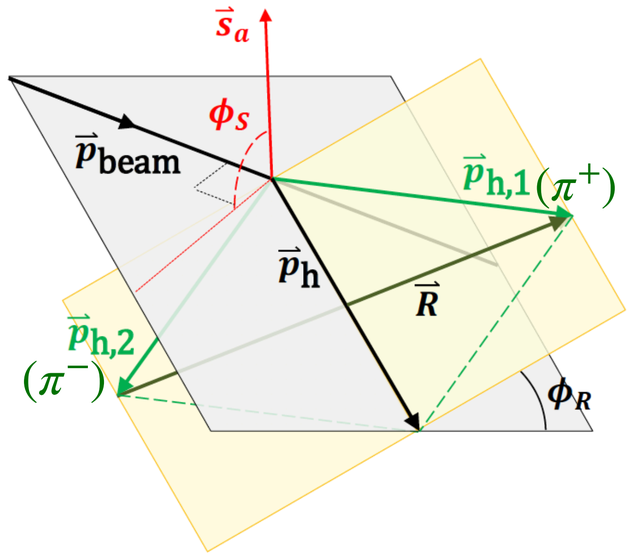
Cross-ratio Method; for A_{UT} Extraction

$$A_{UT} sin(\phi_S - \phi_R) = \frac{1}{P} \frac{\sqrt{N^{\uparrow}_{1,\alpha} N^{\downarrow}_{1,\beta}} - \sqrt{N^{\downarrow}_{1,\alpha} N^{\uparrow}_{1,\beta}}}{\sqrt{N^{\uparrow}_{1,\alpha} N^{\downarrow}_{1,\beta}} + \sqrt{N^{\downarrow}_{1,\alpha} N^{\uparrow}_{1,\beta}}}$$

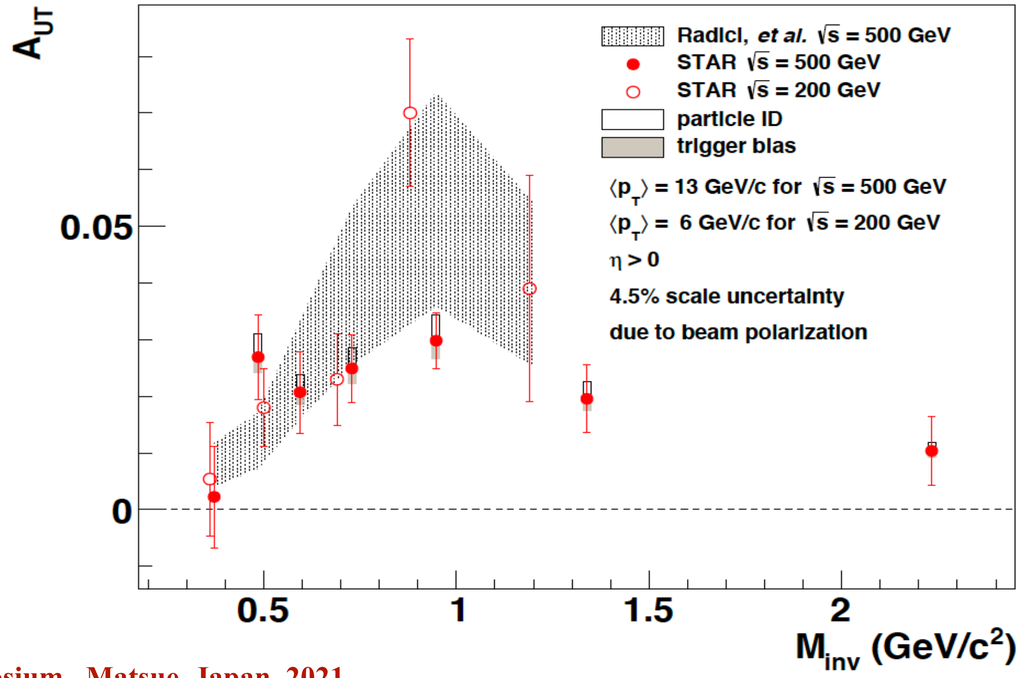
- $N^{\uparrow(\downarrow)}_{1,\alpha(\beta)} \rightarrow$ Number of $\pi^+\pi^-$ in upper, α (lower, β), half of detector when spin direction is Up($\uparrow$) (Down ($\downarrow$)).
- P is average beam polarization.

In this approach, all the detector acceptance effect and the relative luminosity terms cancel out, reducing the systematic uncertainties.

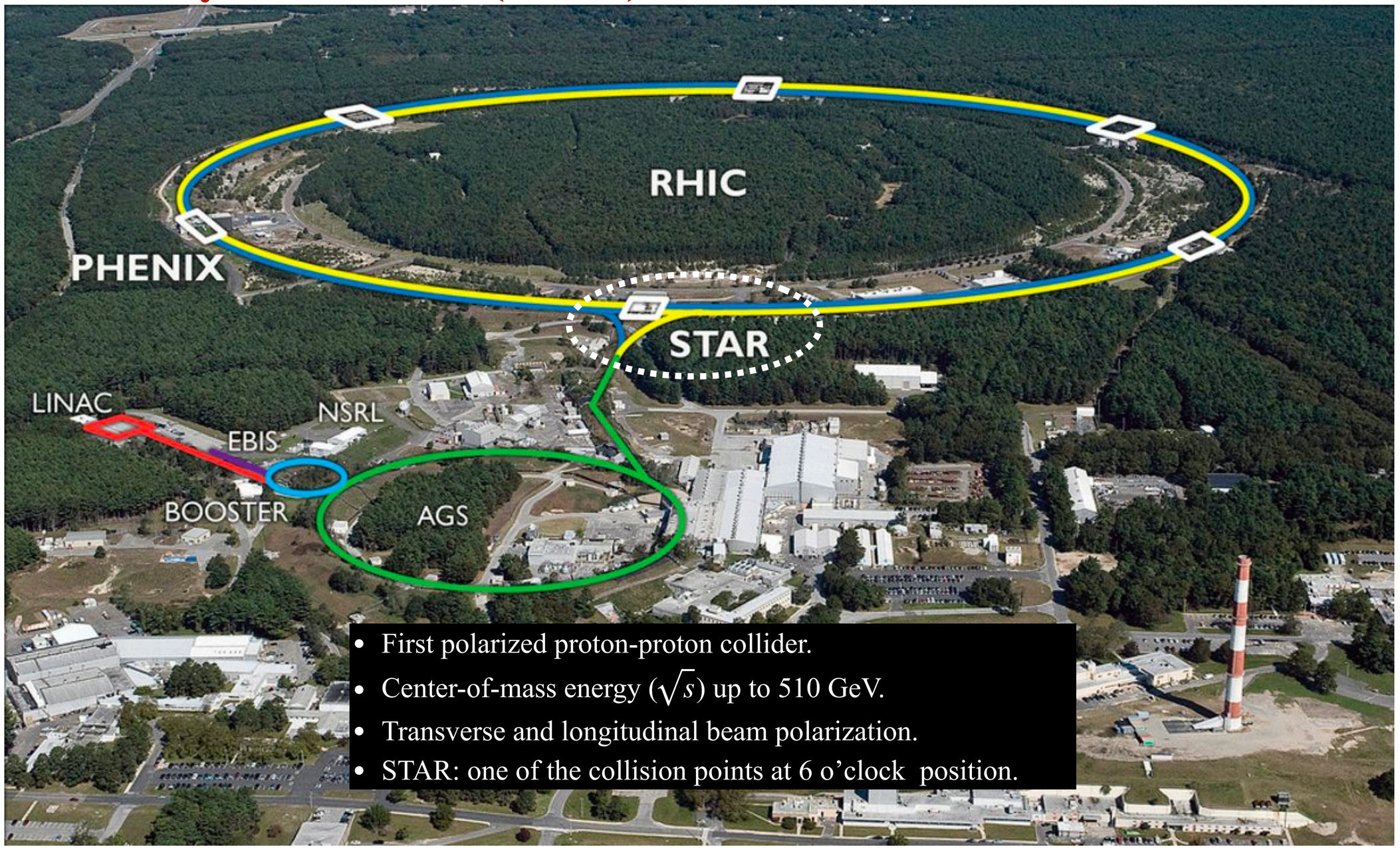
- STAR observed significant $\pi^+\pi^-$ correlation asymmetry, A_{UT}, using 200 GeV and 500 GeV $p^{\uparrow}p$ datasets.
- Although the results are encouraging, statistical errors are large due to limited data sample size.



STAR publications:
- *Phys. Lett. B 780 (2018) 332*
- *Phys. Rev. Lett. 115 (2015) 242501*

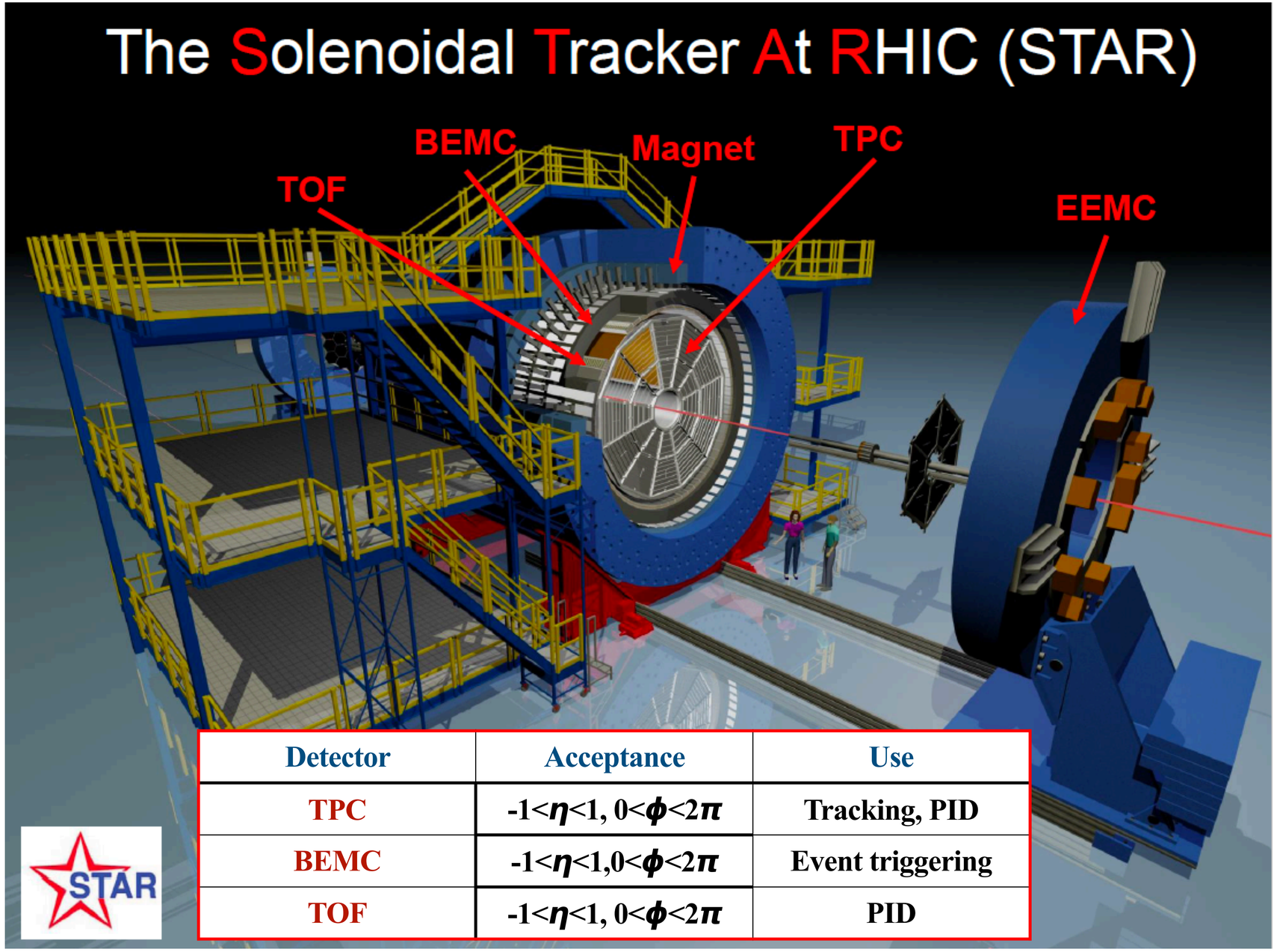


Relativistic Heavy Ion Collider (RHIC)



- First polarized proton-proton collider.
- Center-of-mass energy ($\sqrt{s}$) up to 510 GeV.
- Transverse and longitudinal beam polarization.
- STAR: one of the collision points at 6 o'clock position.

STAR Experiment at RHIC



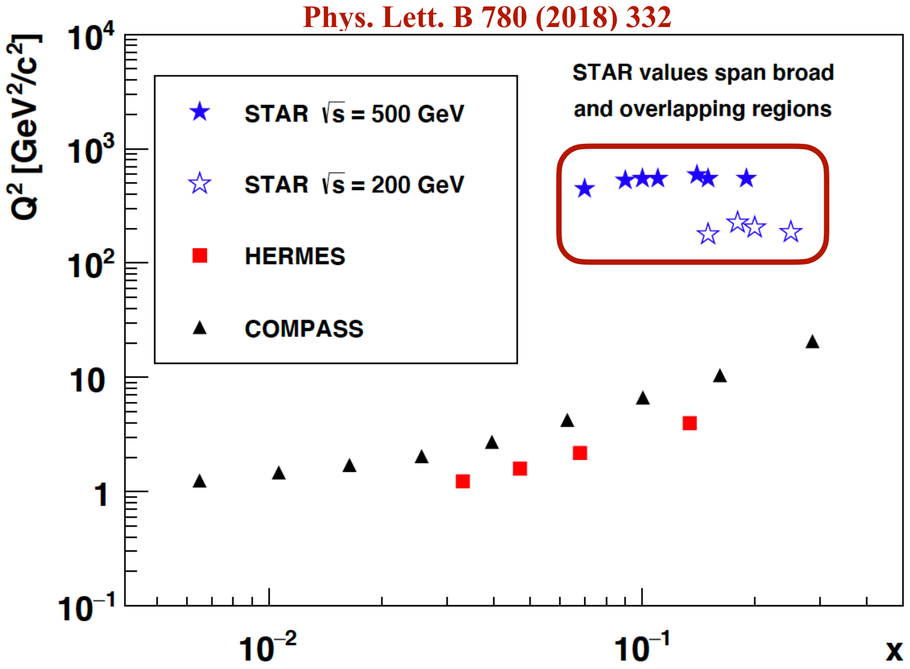
Detector	Acceptance	Use
TPC	$-1<\eta<1,\ 0<\phi<2\pi$	Tracking, PID
BEMC	$-1<\eta<1, 0<\phi<2\pi$	Event triggering
TOF	$-1<\eta<1,\ 0<\phi<2\pi$	PID

STAR Polarized Proton-Proton Dataset

Collision	proton-proton			
Polarization	transverse			
Year	2006	2011	2015	2017
$\sqrt{s}$ (GeV)	200	500	200	510
L_{int} (pb^{-1})	~1.8	~25	~52	~350
$< P_{beam} > (\%)$	~60	~53	~57	~58

This Measurement

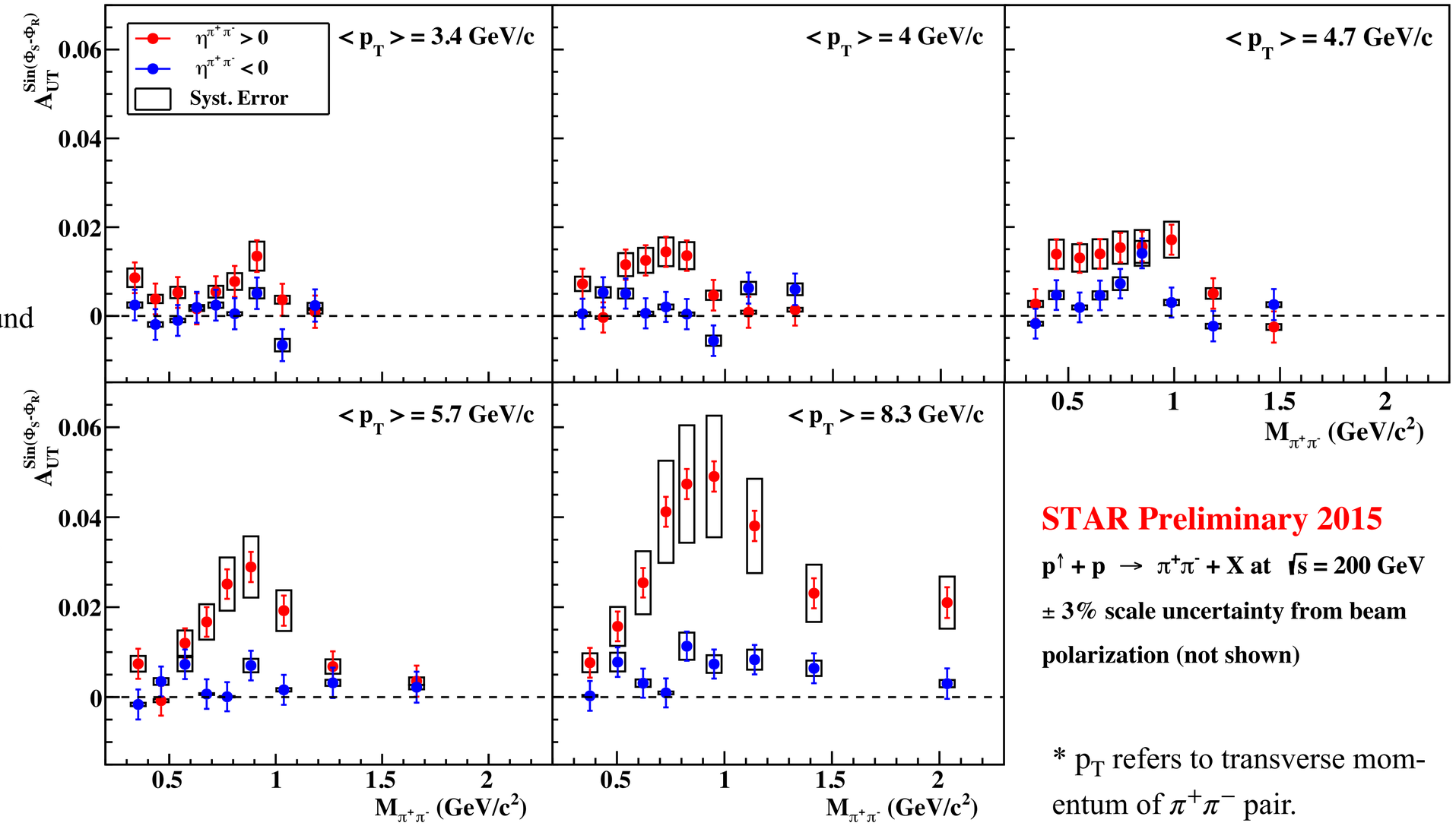
Phys. Lett. B 780 (2018) 332



- STAR Kinematic Coverage:
  - Covers much higher Q^2 than HERMES and COMPASS.
  - Intermediate *x* coverage, valence quark region.

STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$

- $A_{UT}^{\sin(\phi_s-\phi_R)}$ **vs** $M_{inv}^{\pi^+\pi^-}$ **in different** p_T **and** $\eta^{\pi^+\pi^-}$ **bins.**
  - Signal grows stronger at higher p_T in forward $\eta^{\pi^+\pi^-}$ region. Resonance peak around $M_{inv}^{\pi^+\pi^-} \sim 0.8$ GeV/$c^2 \sim M_\rho$.
  - Backward $\eta^{\pi^+\pi^-}$ signal is small, mainly from low x quarks from polarized beam.
- Systematic uncertainty includes effects related to PID and trigger bias.



STAR Preliminary 2015

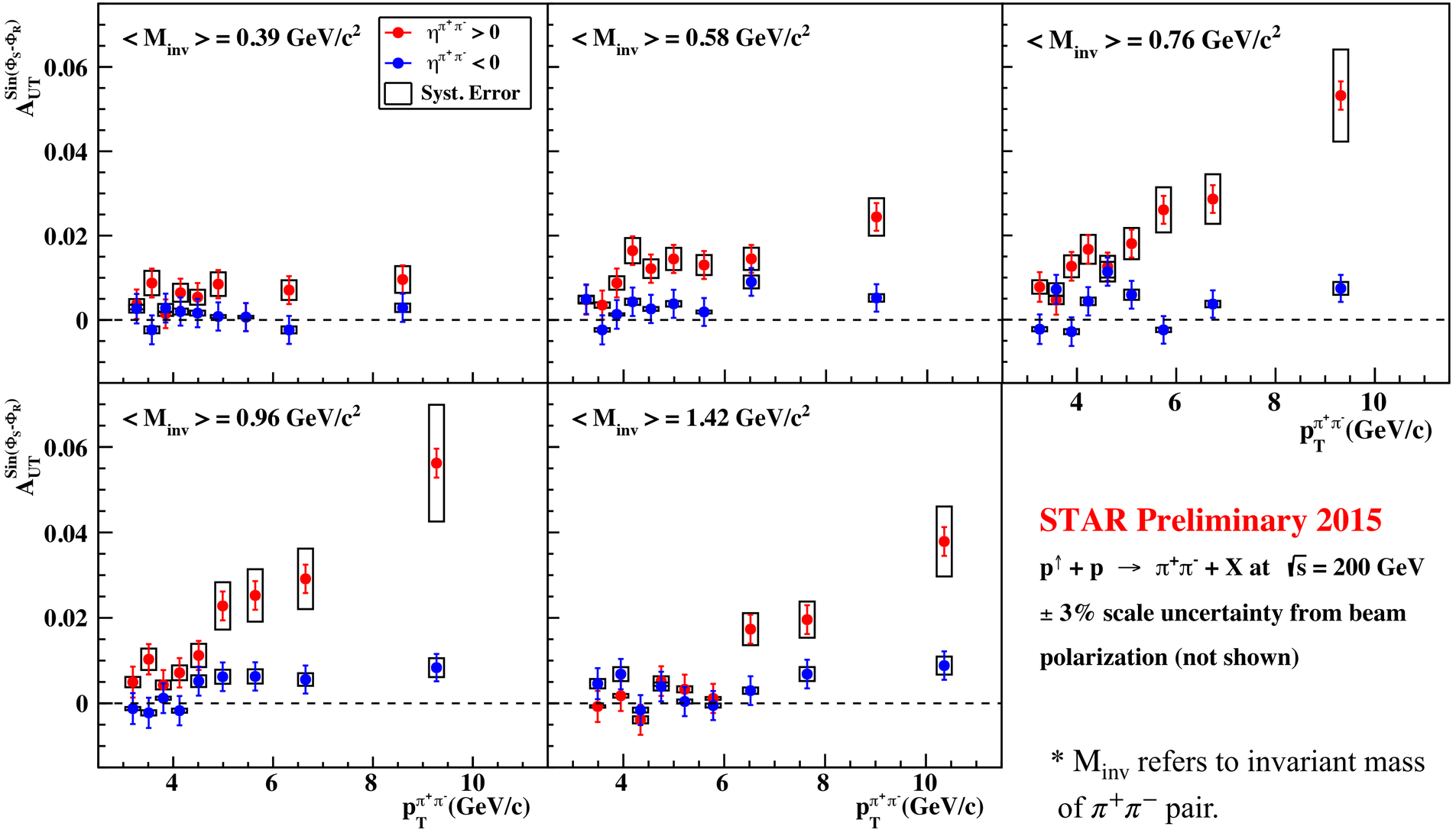
$p^\uparrow + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

± 3% scale uncertainty from beam polarization (not shown)

* p_T refers to transverse momentum of $\pi^+\pi^-$ pair.

STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $p_T^{\pi^+\pi^-}$

- $A_{UT}^{\sin(\phi_s-\phi_R)}$ **vs** $p_T^{\pi^+\pi^-}$ **in different** M_{inv} **and** $\eta^{\pi^+\pi^-}$ **bins.**
  - Large asymmetry signal at higher p_T in forward $\eta^{\pi^+\pi^-}$ region. Stronger signal when $< M_{inv} > \sim M_\rho$.
  - Backward $\eta^{\pi^+\pi^-}$ signal is small, mainly from low x quarks from polarized beam.
- Systematic uncertainty includes effects related to PID and trigger bias.



STAR Preliminary 2015

$p^\uparrow + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

± 3% scale uncertainty from beam polarization (not shown)

* M_{inv} refers to invariant mass of $\pi^+\pi^-$ pair.

STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $\eta^{\pi^+\pi^-}$

Top Panel:

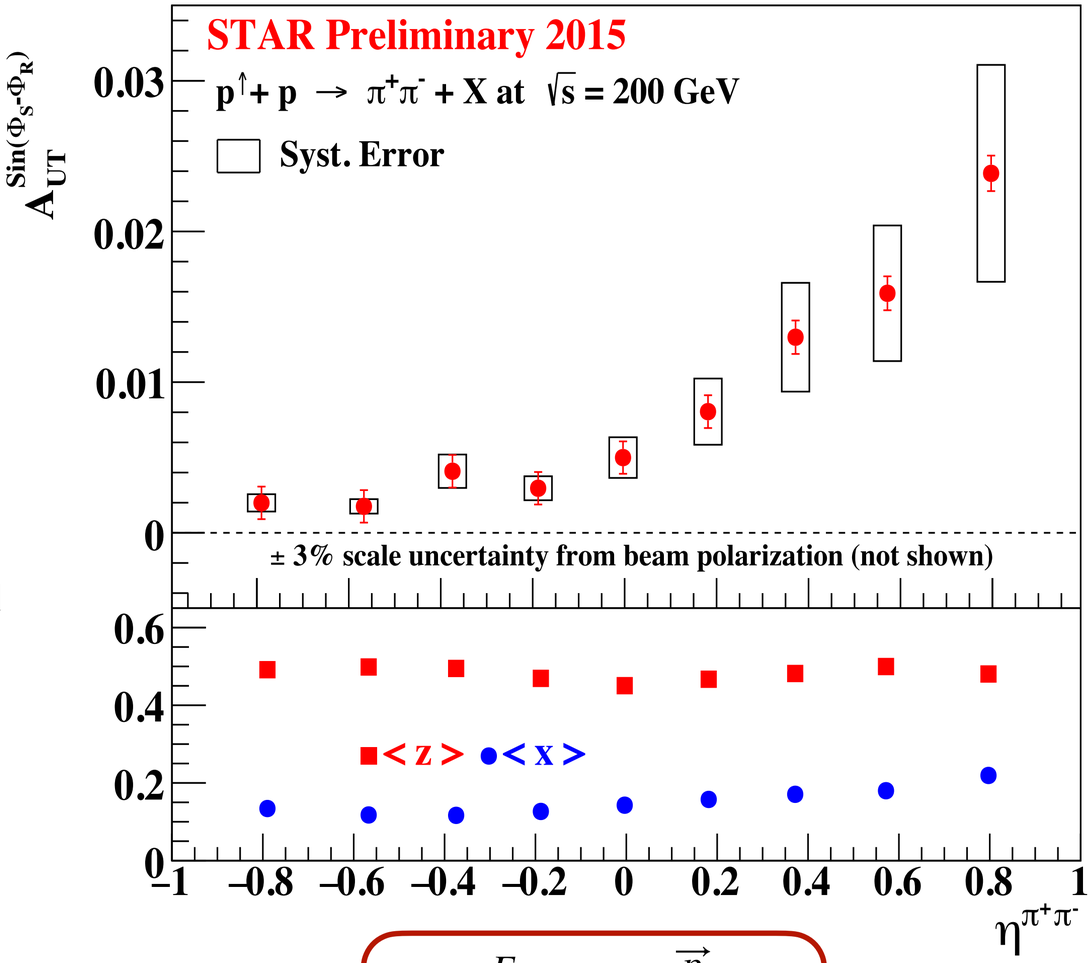
- A_{UT} as a function of $\eta^{\pi^+\pi^-}$ with $p_T^{\pi^+\pi^-}$ and $M_{inv}^{\pi^+\pi^-}$ integrated.

Bottom Panel:

- x, fractional momentum of proton carried by quark, and z, fractional energy of struck quark carried by $\pi^+\pi^-$, as a function of $\eta^{\pi^+\pi^-}$.
- x and z are estimated from simulation.

- **$\eta^{\pi^+\pi^-} > 0$ → higher x quarks → large asymmetry signal**
- **$\eta^{\pi^+\pi^-} < 0$ → low x quarks → small asymmetry signal**

- Systematic uncertainty includes effects related to PID and trigger bias.



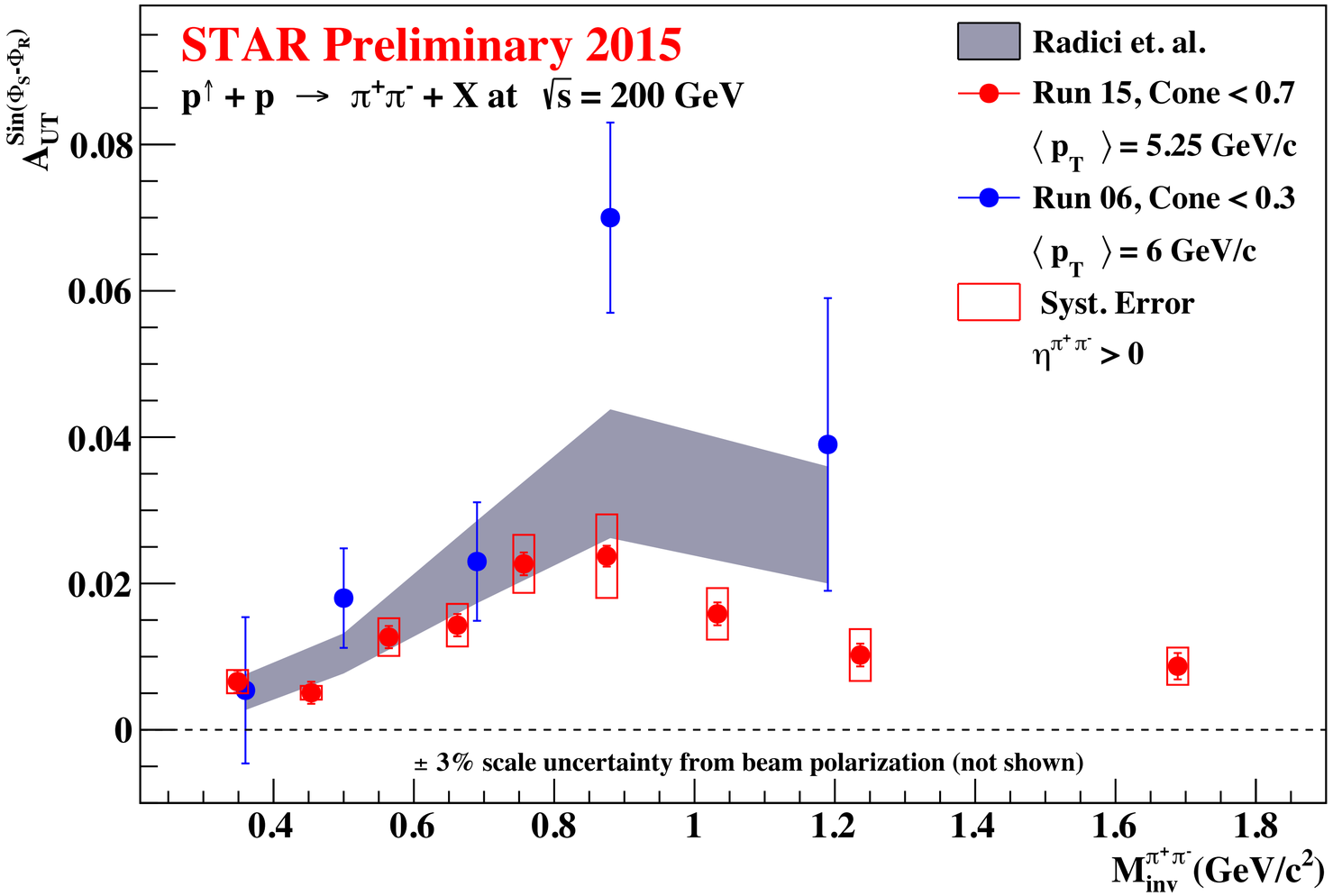
$$z \to \frac{E_{\pi^+\pi^-}}{E_{quark}},\ x = \frac{\vec{p}_{\,quark}}{\vec{p}_{\,proton}}$$

STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $M_{inv}^{\pi^+\pi^-}$, $p_T^{\pi^+\pi^-}$ Integrated

$A_{UT}^{\sin(\phi_s-\phi_R)}$ **vs** $M_{inv}^{\pi^+\pi^-}$ **integrated over** $p_T^{\pi^+\pi^-}$ **in** $\eta^{\pi^+\pi^-} > 0$**:**

- Asymmetry is enhanced around $M_{inv}^{\pi^+\pi^-} \sim 0.8$, consistent with the previous measurement with improved precision and the theory.

- Systematic uncertainty includes effects related to PID and trigger bias.



Summary

- **$\pi^+\pi^-$ azimuthal correlation asymmetries, sensitive to the transversity, have been measured.**
  - In $M_{inv}^{\pi^+\pi^-}$ bins, large forward asymmetries with a prominent peak at $M_{inv}^{\pi^+\pi^-} \sim M_\rho$, consistent with the theory.
  - In $p_T^{\pi^+\pi^-}$ bins, asymmetry increases linearly at high $p_T^{\pi^+\pi^-}$. Asymmetry signal is more prominent when $M_{inv}^{\pi^+\pi^-} \sim M_\rho$.
  - In $\eta^{\pi^+\pi^-}$ bins, integrated over $p_T^{\pi^+\pi^-}$ and $M_{inv}^{\pi^+\pi^-}$, asymmetry signal increases linearly in $\eta^{\pi^+\pi^-} > 0$ region, where **quarks with larger *x*** can be probed. Smaller asymmetry signal in $\eta^{\pi^+\pi^-} < 0$ is due to ***low x quarks*** from polarized beam.
- The **statistical precision** of the new 2015 results is **significantly improved** compared to the previous STAR measurements.
- Further improvements in PID systematic uncertainties expected with improved PID method based on TOF ***(In progress)***.
- These results can be used to **test the universality** between SIDIS, e^+e^-, and $p^\uparrow p$, and **further constrain the global fits**, especially at high x (> 0.1) region.
- Ongoing IFF analysis using the 2017 dataset at $\sqrt{s} = 510$ GeV ($L_{int} \sim 350$ pb^{-1}, ~ 14 times larger than 2011 dataset).
- **Planned unpolarized di-hadron cross-section measurement**, combined with these high precision asymmetry results, will help to constrain transversity.